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AUTOMATIC CONTROL OF THE TERMINAL VOLTAGE OF A
12.5-KVA ALTERNATOR

069

by
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AN ESSAY

Submitted to the Advisory Board of The School
of Engineering, The Johns Hopkins University
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degree of Master of Engineering.

Baltimore

1949

Thesis

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RESEARCH REPORT

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ACKNOWLEDGMENTS

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APPENDIX

The most recently completed and revised
of these is that of the 1950-51 season. It
was prepared by the same person who
prepared the 1949-50 season. The 1949-50
season was the last season for which
data is available. The 1950-51 season
was the first season for which data
is available. The data for the 1950-51
season is given in the table below.

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INTRODUCTION

The increasing need for an automatic voltage regulator to meet the exacting requirements of industrial and laboratory service has led to innumerable attempts to produce a device which will keep the terminal voltage of an alternator constant as the load is varied. If an alternator has its field current adjusted so as to supply rated voltage at no-load and rated frequency, the terminal voltage decreases as resistive or inductive loads are applied and increases as capacitive loads are applied to the machine. In order to prevent this the generated voltage of the machine must be controlled by controlling the field current to compensate for the variable impedance drop and the variable demagnetizing effects.

The first successful attempts at automatic control of the terminal voltage of alternators were made with various types of vibrating contact devices such as the D'Arsonville regulator.¹⁴ In addition to their being relatively slow in response to the changing loads, the deterioration by use of the moving parts and the necessary frequent adjustment made them undesirable. It was not until the grid-controlled mercury rectifier tube was developed that a basis was provided for improving the voltage regulator. Electronic voltage regulators provide practically instantaneous response without the use of moving parts.

The purpose of this paper is to discuss the design, construction and performance of an electronic voltage regulator for a 12.5-kva laboratory alternator. The alternator is to be used as a power supply for undergraduate experiments on a 5-kva synchronous motor. The generator is driven by a 15-hp, compound-wound direct current motor. The synchronous motor experiments require constant voltage for loads up to 7.5-kva for a range of power factor between 0.5 lagging and 0.5 leading. This essay includes a brief survey of voltage regulator circuits as well as the solution of the above problem.

The purpose of this paper is to discuss the results

concerning the results of the experiments on the

effect of the temperature on the rate of the

reaction. It is found that the rate of the

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results are shown in the following table.

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A BRIEF SURVEY OF AVAILABLE CIRCUIT ARRANGEMENTS
FOR ELECTRONIC VOLTAGE REGULATORS

The gas-filled triode or thyatron is the most important component of an electronic voltage regulator. Its usefulness lies in its low, constant, internal voltage drop and the resulting high circuit efficiency for large currents. However, the ionization of the gas which permits this low drop also prevents the control grid from stopping the flow after it has once begun. Therefore, the usual application of thyatrons is on an alternating current system where the periodic reversal of the anode voltage permits deionization and a chance for the grid to regain control. After current has ceased flowing upon the reversal of the anode voltage and subsequent deionization, a negative grid will prevent its restarting even though the anode has again become positive. It is possible to operate the grid of a thyatron from a direct current supply, but to obtain smooth control, it is necessary to use firing circuits which operate wholly or partially from the same alternating current supply used for the anode circuit.

The basic parts of a voltage regulator are:

- (1) Voltage-sensitive circuit
- (2) Control circuit
- (3) Thyatron circuit
- (4) Antihunting circuit

A BRIEF HISTORY OF THE UNITED STATES

THE EARLY YEARS

The first English colony in America was founded in 1607.

That settlement was on Jamestown, Virginia. The

settlement was for 121 years, but it was not

and the people died of starvation. The first

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Probably the first voltage sensitive circuit used in an electronic voltage regulator was the non-linear bridge. This bridge has been used in many forms, but the most common appears to be the lamp bridge. This is shown in Fig. 1 where R_1 and R_2 are tungsten lamps and R_3 and R_4 are carbon lamps. It operates on the principle that the resistance of tungsten increases with increasing temperature while the resistance of carbon decreases with increasing temperature. Therefore there is only one value of applied voltage for which the bridge is balanced. The output voltage for an input less than that required for balance is out of phase by 180° to the output for an input voltage greater than the balance value. This circuit has been used successfully by Weinland² and Benson^{6,7}. A variation of this bridge whereby linear resistors replace lamps in opposite arms, as R_3 and R_4 , has been used by Hull¹ and Richter¹³. Another type of non-linear bridge was used by Shipple and Jacobsen⁴ and is shown in Fig. 2. The values of the circuit parameters were such that the output was extremely sensitive at the value of voltage to be regulated (120 volts) as shown in Fig. 3.

Gulliksen⁵ describes another type of voltage-sensitive circuit in which the terminal voltage of the alternator supplies voltage through a transformer to the tung-

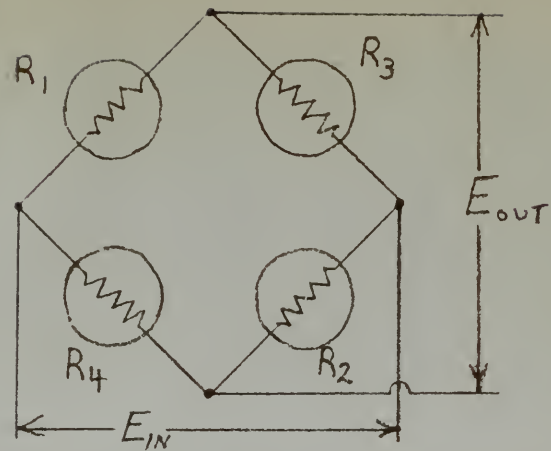


FIG. 1 - NON-LINEAR LAMP BRIDGE

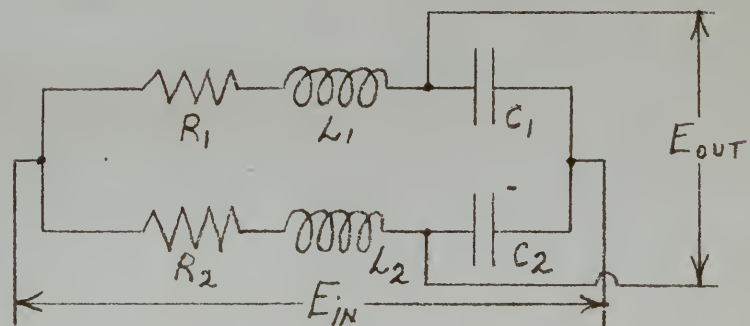
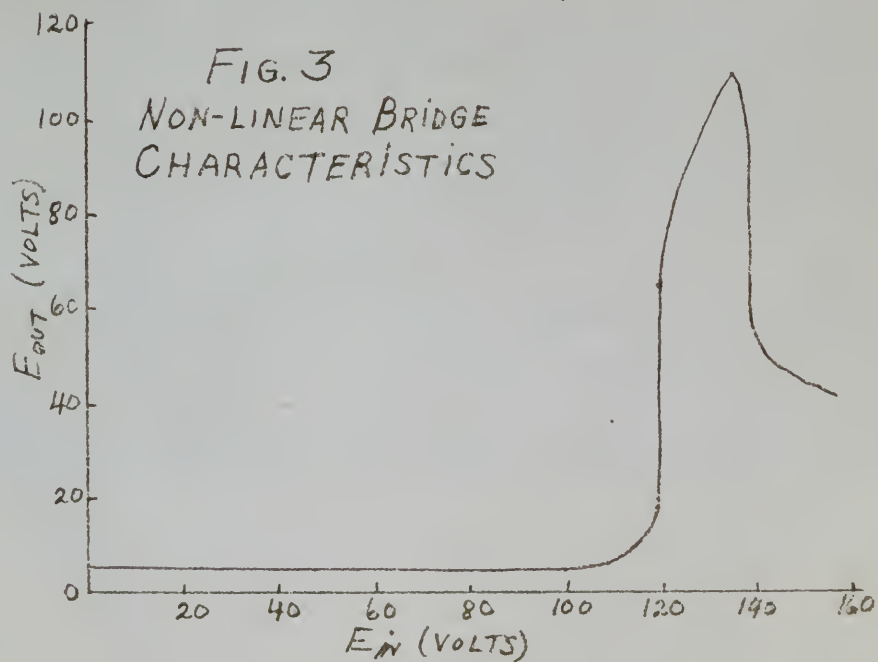


FIG. 2 - NON-LINEAR BRIDGE



sten filament of a high vacuum diode, operating at an anode voltage which exceeds the saturating voltage so that anode current will be controlled by the filament temperature and consequently the filament voltage. The disadvantage of this circuit and the lamp bridge circuit is that response is not instantaneous due to a small thermal lag.

The most popular voltage-sensitive device is the full-wave rectifier and filter which detects instantly any change in the alternator terminal voltage, the output being direct current. This circuit is used for controlling the grid circuit of a thyatron by shifting the phase of the grid voltage as will be explained later.

There are three fundamental methods of controlling the grids of thyatrons in voltage regulators using alternating current.

- (1) Phase shift of the grid voltage (with respect to the anode voltage).
- (2) A fixed phase alternating voltage superimposed upon a variable unidirectional voltage.
- (3) The magnitude method which is associated with the lamp bridge.

The phase shifter usually consists of a resistance-reactance circuit. Phase shift is obtained by varying the resistance which may be a triode vacuum tube whose grid bias

is varied by a unidirectional voltage proportional to the alternator output. Likewise the reactance may be varied (and this is commonly done) by the use of a saturable reactor whose saturation is likewise controlled by a direct current voltage similar to the above. Various phase control circuits are explained in papers by Cockrell⁸, Chin⁹, May, Reich, Skalnik¹⁰, and Annett¹¹.

Cockrell⁸ describes a fixed a.c. with a variable d.c. circuit in which an alternating current of fixed amplitude from the anode supply is made to lag the anode voltage by 90° and the direct current bias is varied in proportion to the terminal voltage. As shown in Fig. 4 this method permits control of the thyatron throughout the positive half of the cycle. At least one of the commercially produced voltage regulators¹¹ employs this method of grid control.

The output of the lamp bridge may be applied directly to the grid of the thyatron and 180° out of phase with the anode voltage, the firing being determined by the amplitude of the grid voltage. This is not desirable due to the fact that the grid has control for only half of the positive half of the cycle as shown in Fig. 5(a). Weinland¹² and Benson^{6,7} used an RC phase shift network such that the grid voltage lagged the anode voltage by an angle slightly less than 180° and obtained a greater degree of

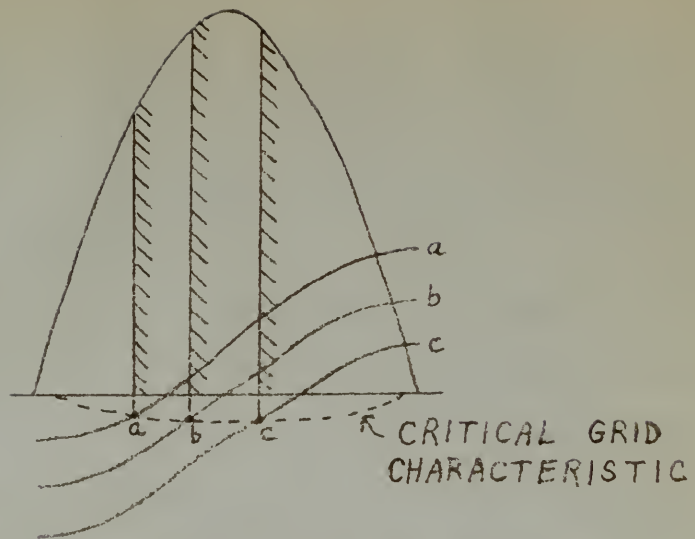


FIG. 4- GRID CONTROL BY FIXED A-C AND VARIABLE D-C. SHADED AREA INDICATES TUBE CONDUCTION.

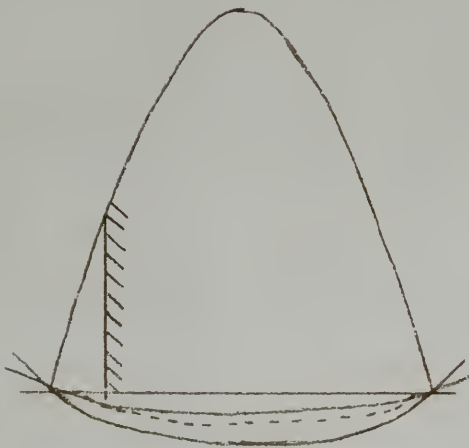


FIG. 5(a)

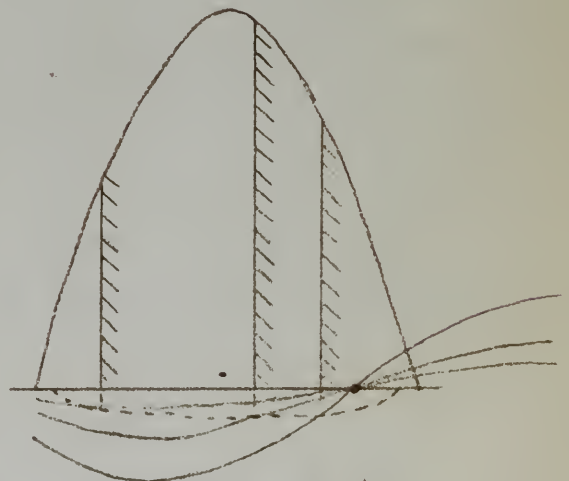


FIG. 5(b)

MAGNITUDE METHOD OF GRID CONTROL

control as shown in Fig. 5(b). Weinland² also obtained greater sensitivity by using a center-tapped step-up transformer and controlling the grids of two thyatron³ connected as a full wave rectifier.

The thyatron circuit consists of the anode supply voltage, the thyatron tube or tubes and the load. Since much better control is obtained when the grid and anode voltages are from the same source, the alternator usually supplies the anode voltage. However, the commercial regulator described in reference 11 is an exception and uses a separate three-phase voltage supply and three thyatrons.

Alternators are usually excited by a small direct current exciter whose rotor is coupled to the alternator shaft. The load in this case is the field circuit of the exciter which requires a great deal less current than the alternator field. Since the current rating of the tubes of a voltage regulator is limited to a few amperes, an exciter is a necessity when regulating the terminal voltage of large alternators. The field current of the exciter or alternator may be controlled by connecting the output of the regulator directly across the field winding, riding or tapping, or may be connected across the field rheostat⁴.

When an exciter is used, the time constants of both the exciter and alternator fields enter and bursting of the terminal voltage may result, necessitating an antihunting

circuit^{8,11}. This is usually an AC circuit connected directly across the alternator field. Current flows through this circuit only when there is a change in the voltage across the field, resulting in a momentary potential rise or drop across the resistance. This momentary potential is applied to the grid of the thyatron in the correct direction to prevent hunting. Reinhold⁸ found that an antihunting circuit was usually unnecessary when the alternator field was controlled directly.

Altogether, this is a very good example of a

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CHARACTERISTICS OF THE ALTERNATOR

The alternator selected for voltage regulation was the Model 11G491 Type ATE manufactured by the General Electric Company (see Fig. 15(a)). It is rated at 12.5 kva, 106 volts, 34.7 amperes, 3-phase at 60 cycles. Field excitation is obtained from a 250 volt d.c. bus. The prime mover is a General Electric Model 35A1501 Type CE compound-wound direct current motor rated at 15-hp, 200 volts, 51 amperes at 1800 RPM. The output of the alternator is not a pure sine wave, but has a pronounced 13rd harmonic ripple. It would have been desirable for the alternator to be driven by a synchronous motor to provide constant speed and consequently a constant frequency output from the alternator. Automatic speed control of the motor will be applied later.

There was no data available on the characteristics of this machine, so it was necessary to conduct tests for the open-circuit and short-circuit characteristics. The results are shown in Fig. 6. These tests were conducted by the usual method described in most standard test books on the subject. In addition the ohmic resistance of the field was measured as 69.5 ohms and the ohmic resistance of the armature as .053 ohms per phase. These values were obtained by the voltmeter-ammeter method.

THE ALIEN ACT

The following is a summary of the provisions of the Act.

The Act is divided into three parts: (1) the definition of an alien, (2) the powers of the Government, and (3) the penalties.

Part I defines an alien as a person who is not a citizen of the United States.

Part II gives the Government the power to exclude or deport any alien who is deemed to be a threat to the national security.

Part III sets out the penalties for anyone who violates the provisions of the Act.

The Act also provides for the establishment of a board of inquiry to hear the cases of aliens who are being considered for deportation.

The Act is intended to protect the United States from the dangers of alien infiltration.

The Act is a very important piece of legislation, and it is essential that it be properly understood.

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12.5-KVA ALTERNATOR
 GENERAL ELECTRIC COMPANY
 MODEL 11G491 TYPE ATB
 208 VOLTS 34.7 AMPERES
 3-PHASE 60-CYCLE

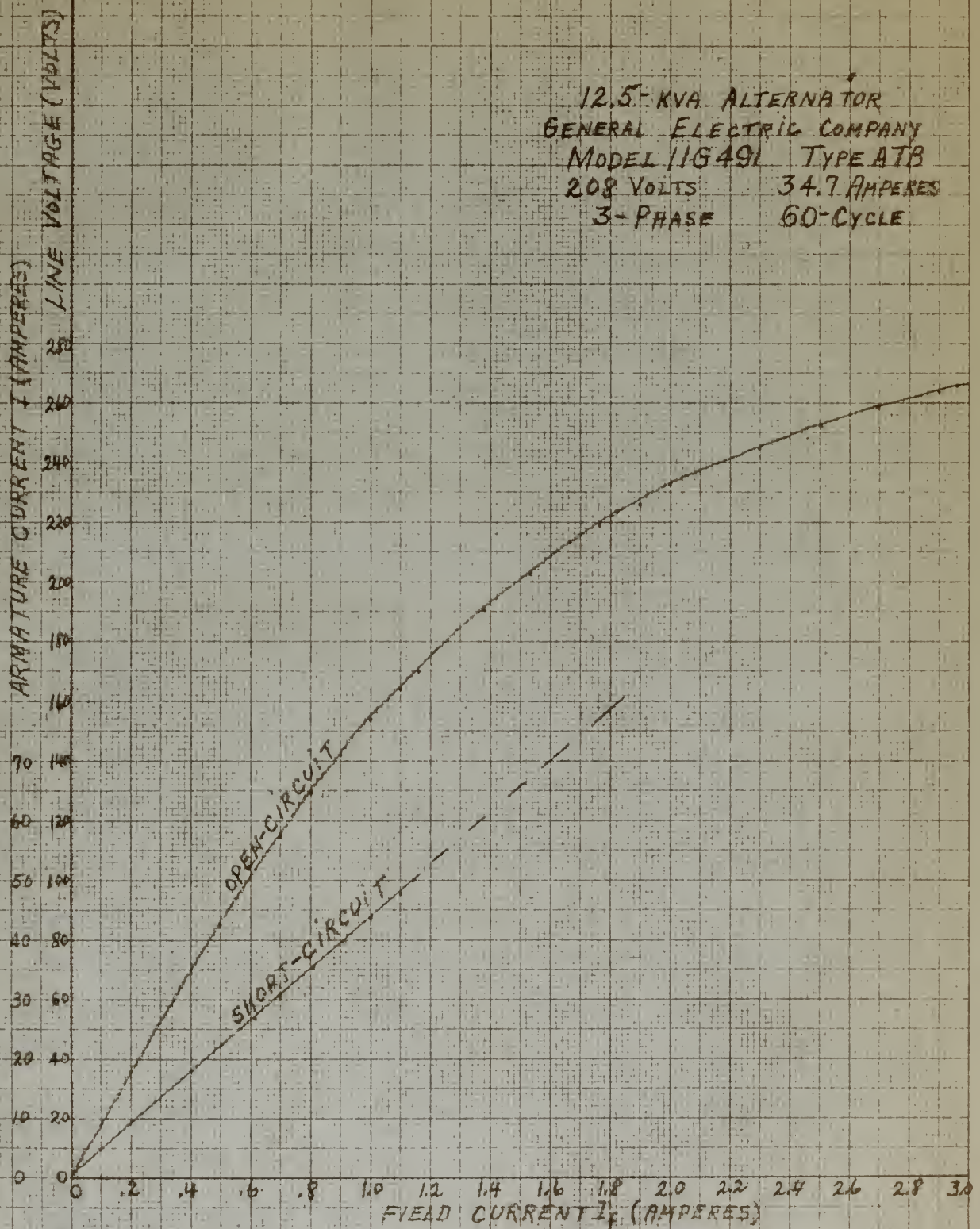


FIG. 6-OPEN-CIRCUIT AND SHORT-CIRCUIT CHARACTERISTICS OF 12.5-KVA ALTERNATOR.

For design purposes the synchronous-impedance or pessimistic Method is satisfactory for calculating the regulation of the alternator since it gives a value of regulation poorer than the actual regulation. The synchronous impedance is calculated at the highest possible value of armature current, usually at twice rated current. From Fig. 6 the field current corresponding to twice rated current is 1.58 amps and the open-circuit voltage corresponding to this value of field current is 206 volts. If it is assumed that this voltage is being used entirely in sending twice rated current through the armature impedance, then the synchronous impedance per phase, Z_s , may be calculated as equal to $\frac{206}{\sqrt{3} \times 60.5} = 1.71$ ohms. This is made up of two components, the effective resistance R_e and the synchronous reactance, X_s . Therefore $X_s = \sqrt{Z_s^2 - R_e^2}$ and since R_e is very small, X_s may be assumed to be equal to Z_s .

The regulation of this machine supplying a 7.5-kva load at unity power factor is calculated as follows:

$$I = \frac{7500}{\sqrt{3} \times 605} = 10.8 \text{ amperes. } V/\text{phase} = \frac{200}{\sqrt{3}} = 120 \text{ volts.}$$

$$R_e \text{ is assumed to be 1.4 times the ohmic resistance } = 1.4 \times .052 = .074 \text{ ohms.}$$

$$E = \sqrt{(V/\text{phase} + IR_e)^2 + (IX_s)^2}$$

$$E = \sqrt{(120 + 20.6 \times .074)^2 + (20.6 \times 1.71)^2}$$

$$E = \sqrt{(121.54)^2 + (35.6)^2} = \sqrt{14700 + 1268}$$

$$E = \sqrt{16048} = 126.8 \text{ volts}$$

$$\text{Regulation} = \frac{126.8 - 120}{120} \times 100 = 5.65\%$$

For 7.5-kva load at 0.5 power factor, lagging

$$E = \sqrt{(V \cos \theta + I R_e)^2 + (V \sin \theta + I X_e)^2}$$

$$E = \sqrt{(120 \times .5 + 20.6 \times .074)^2 + (120 \times .866 + 20.6 \times 1.71)^2}$$

$$E = \sqrt{(80 + 1.54)^2 + (104 + 35.6)^2} = \sqrt{3600 + 18300}$$

$$E = \sqrt{21900} = 152.5 \text{ volts}$$

$$\text{Regulation} = \frac{152.5 - 120}{120} \times 100 = 27.1\%$$

For 7.5-kva load at 0.5 power factor, leading

$$E = \sqrt{(V \cos \theta + I R_e)^2 + (V \sin \theta - I X_e)^2}$$

$$E = \sqrt{3600 + (104 - 35.6)^2} = \sqrt{3600 + 864}$$

$$E = \sqrt{3600 + 4670} = \sqrt{8270} = 92 \text{ volts}$$

$$\text{Regulation} = \frac{92 - 120}{120} \times 100 = -23.3\%$$

$$z = \sqrt{(120.0 + 0.0) + (0.0 + 0.0)} = 0.0$$

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$$z = \sqrt{(120.0 + 0.0) + (0.0 + 0.0)} = 0.0$$

For 7.5-sec load at 0.5 sec from start, loading

$$z = \sqrt{(120.0 + 0.0) + (0.0 + 0.0)} = 0.0$$

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For 7.5-sec load at 0.5 sec from start, loading

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$$z = \sqrt{(120.0 + 0.0) + (0.0 + 0.0)} = 0.0$$

ESTABLISHMENT OF THE LOAD RANGE AND

RANGE OF POWER FACTOR

The synchronous motors which will receive their power from this alternator are rated at 3-kva and it is not anticipated to use more than one as a load on this alternator at any one time. The synchronous motor will seldom be required to operate with more than 50% overload so the load range was set at 7.5-kva.

The alternator field is rated at 2.5 amperes and it should not be operated at a value very much higher than this for any long period of time. However, it is believed that a maximum field current of 3 amperes would not be harmful to the field winding.

In the preceding section the generated phase voltage was calculated for a 7.5-kva load at 0.5 power factor, lagging and leading. The values correspond to line voltages of 264 volts for the lagging case and 159 volts for the leading case. From the characteristic curves of Fig. 6 these require field currents of 2.9 and 1.05 amperes respectively. Since the maximum field current has been set at 3 amperes, the extreme lagging power factor that can be obtained is slightly less than 0.5. There is no limit for leading power factors at 7.5-kva, but it is not anticipated that it will be less than 0.5.

THEORY OF THE EARTH

CHAPTER IV

The atmosphere is a gas which fills the space between the

surface of the earth and the outer limit of the atmosphere.

It is composed of a mixture of gases and vapors.

The atmosphere is a gas which fills the space between the

surface of the earth and the outer limit of the atmosphere.

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The atmosphere is a gas which fills the space between the

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In the atmosphere, the air is composed of a mixture of

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vapors. The atmosphere is a gas which fills the space

In order to see more clearly the load and power factor ranges of the alternator for a maximum field current of 3 amperes, a simple diagram may be constructed in which the armature resistance effect is neglected as in Fig. 7. Thus it is seen that approximately full load may be obtained at 0.9 leading, 10-kva at 0.8 leading, 2-kva at 0.7 leading and 2.5-kva at 0.6 leading. Therefore, a regulator that is capable of supplying current up to 3 amperes will give regulation over a fairly wide range of loads and power factors.

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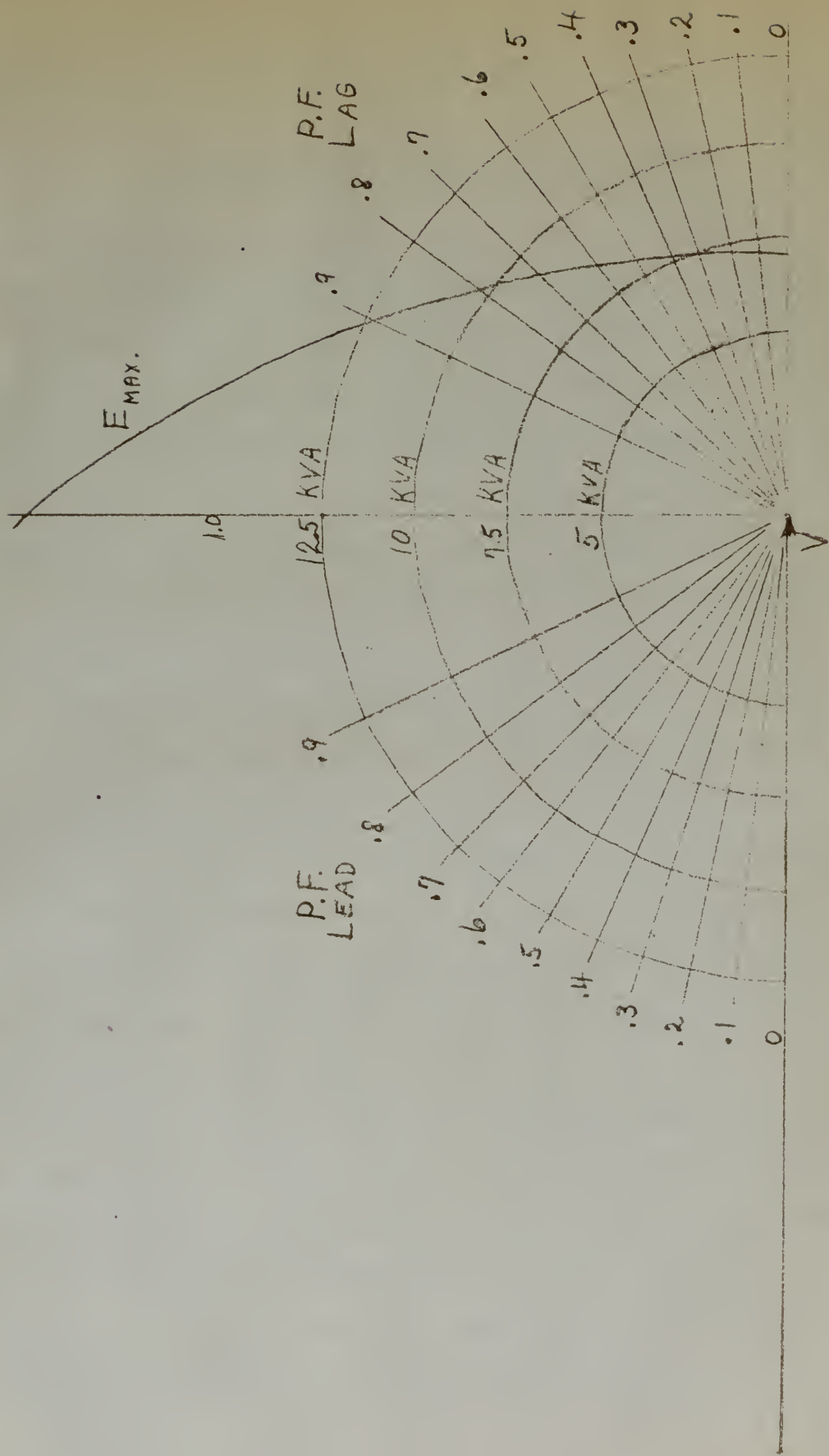


FIG. 7. - DIAGRAM OF LOAD AND POWER FACTOR RANGE FOR
 MAXIMUM FIELD CURRENT OF 3 AMPERES. (APPROXIMATE
 SINCE EFFECT OF ARMATURE RESISTANCE IS NEGLECTED).

SELECTION BY CIRCUIT ARRANGEMENT

It was desired that the circuit arrangement of the voltage regulator contain as few components as possible and yet maintain the terminal voltage nearly constant over the range determined in the preceding section. The components should be of the standard types available at an economical price, but should be rugged enough such that replacement will be required only after long periods of use. Furthermore, the necessary adjustments for proper operation of the regulator should be few and simple.

As explained in a previous section, better regulation can be obtained when the regulator is operated from the regulated supply voltage. In order to prevent possible distortion of the alternator terminal voltage, the regulator should conduct current on both positive and negative halves of the cycle. Two thyratrons connected as a full wave rectifier form a convenient arrangement and in addition this produces a rectified current with a wave form which is much more desirable than that obtained from a half-wave arrangement. Since the maximum average current rating of thyratrons seldom exceeds 4.5 amperes and the current requirement of the regulator is 3 amperes, it would be impossible to manage with only one tube, even if half-wave rectification proved to be satisfactory.

REVISION OF CIVIL ENGINEERING

It was desired that the object-arrangement of the
 voltage regulation should be the same as in the
 and yet maintain the original voltage level.
 over the range indicated in the original circuit.
 components should be at the same time available as
 an automatic system, and having no moving parts and
 replacement will be required only after long periods of
 use. Furthermore, the necessary adjustment for
 operation of the regulator should be for one value.

As explained in a previous section, before regulation
 can be obtained from the regulator in question there is a
 regulated output voltage. In order to obtain results
 distribution of the electrical energy, the regulator
 should maintain constant voltage in each branch and should deliver
 of the total. The distribution is shown in a table
 regulated from a regulated system and in addition
 this provides a regulated output and a regulated input.
 It was now required that the regulator have a regulated
 arrangement. Since the voltage across the output
 of the system which exceeds 1.5 volts and the output
 requirement of the regulator is 1.5 volts, it was
 impossible to obtain this with one stage, and it was
 now regulation proved to be satisfactory.

In view of the fact that the regulator is required to regulate the terminal voltage when the load draws a leading current, a condition which may require a smaller field current than is required at no-load, the regulator must supply all current necessary in excess of that required at a power factor of 0.5, leading. The best solution appears to be to connect the output of the regulator directly across the alternator field, aiding the excitation current and to decrease the value of field current supplied by the D.C. bus by means of the field rheostat after the regulator has been placed in operation.

The lamp bridge is the simplest and cheapest to construct of the existing voltage-sensitive circuits. It has the added advantage that the output may be applied directly to the grid of the thyatron through a center-tapped transformer in the case of full-wave rectification without the use of a phase shifting circuit, as will be explained later.

This arrangement does not require a battery for grid bias or as a reference voltage as many existing regulators do. This eliminates another item of initial expense and cost of maintenance.

In view of Weinland's² findings that an autotuning circuit is not necessary when the regulator controls the alternator field directly, this circuit was not included.

[illegible]

DESIGN OF THE CIRCUIT

The alternator armature is Y-connected with all four leads terminating at the panel board and the neutral is not grounded. The line voltage is 408 volts and the phase voltage is 240 volts. This value of phase voltage allows the standard filament transformers that are commercially available to be used for heating the filaments of the thyatrons. As shown in Fig. 8 there are voltages of a number of different phase relations available and those differing by 150° may be used to good advantage as the anode supply voltage and the voltage input to the lamp bridge, thus eliminating the necessity of a phase shift network.

Voltage-sensitive Circuit:

The voltage vs. resistance characteristics of carbon and tungsten lamps are reproduced in Fig. 9. The point of intersection of the curves of a tungsten and carbon lamp indicates the voltage at which the resistances of the two lamps are equal. If these lamps were used in the lamp bridge, twice this voltage would be the value required to balance the bridge. Also the greater the angle of intersection the more sensitive the bridge will be. Since it is desired to use the phase voltage of 240 volts as the input to the bridge, the 75 watt tungsten and 150

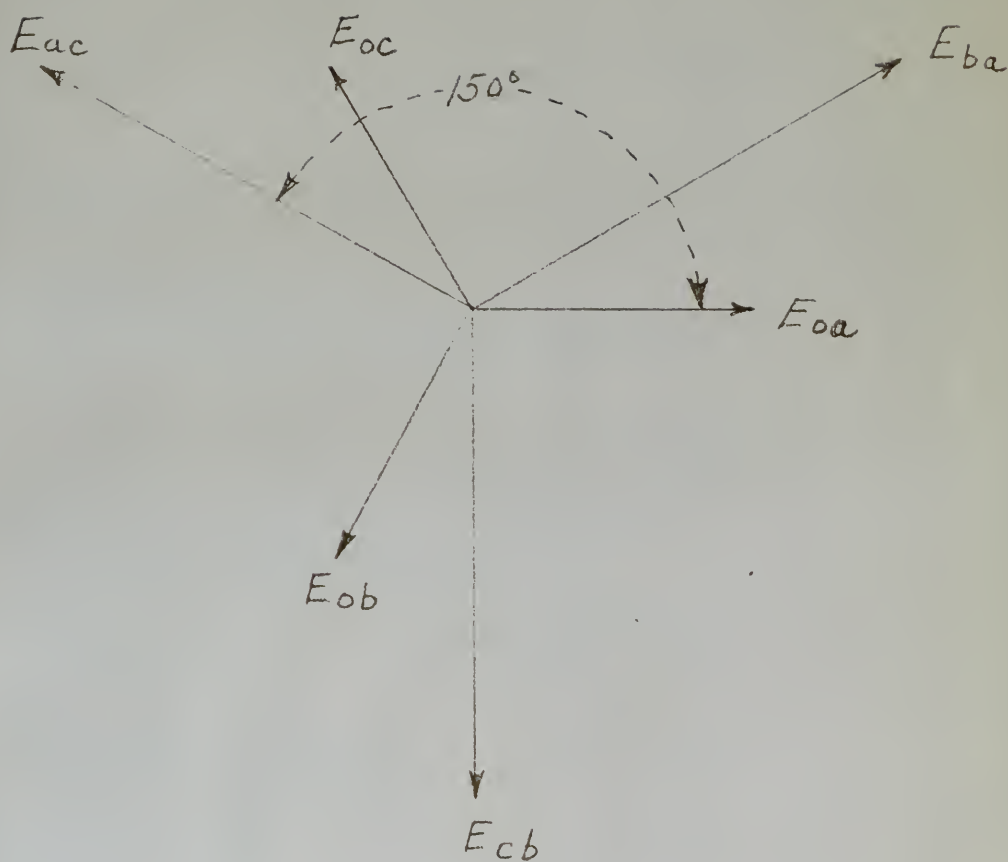


FIG. 8-PHASE RELATION OF LINE AND PHASE VOLTAGES OF ALTERNATOR.

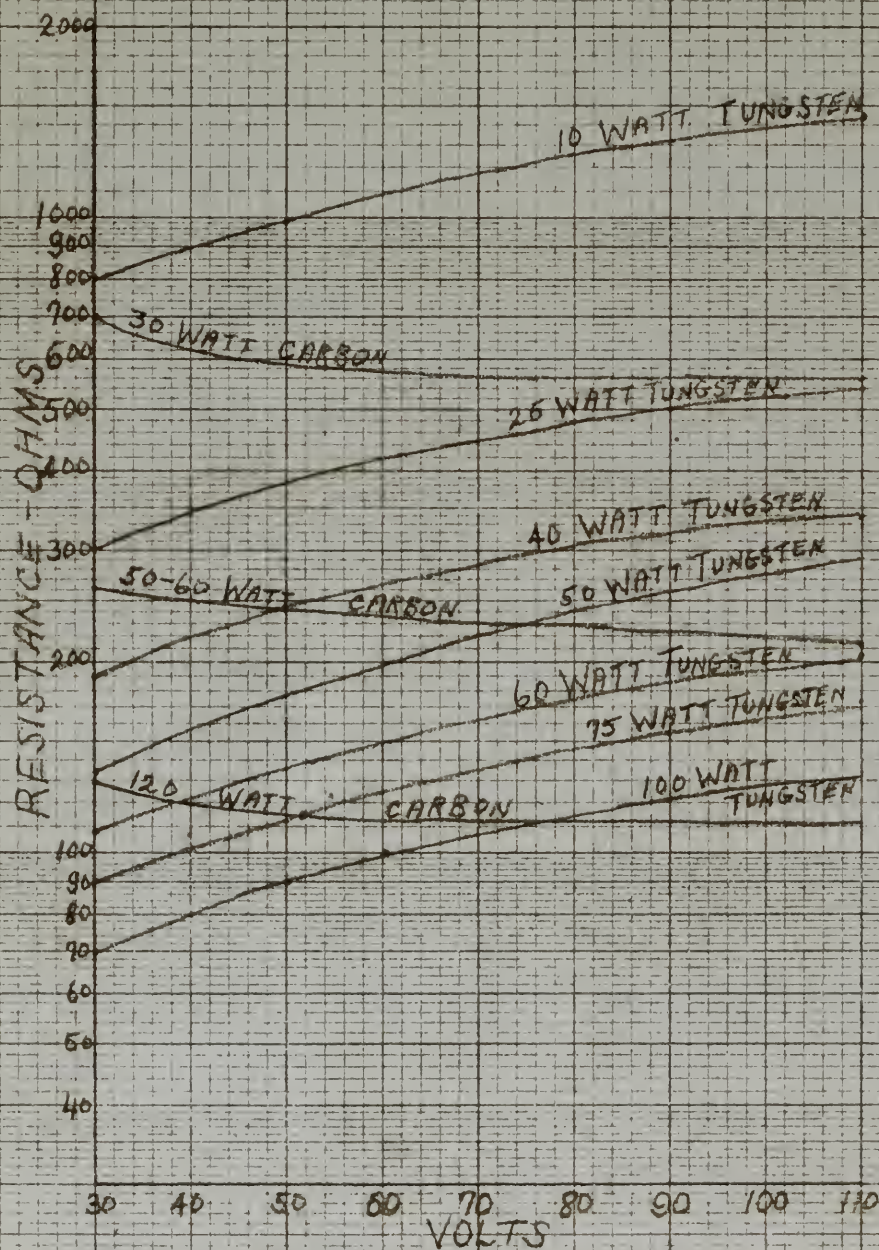


FIG. 9 - VOLTAGE vs. RESISTANCE CHARACTERISTICS OF CARBON AND TUNGSTEN LAMPS.

watt or 3E C.B. carbon combination appears to be the best, giving a balance at 103 volts. The voltage characteristics of this Bridge is shown in Fig. 10. At balance each lamp requires .45 amperes or the total current required from the alternator is .9 amperes. Therefore a standard 25 ohm, 25 watt potentiometer in the voltage sensitive circuit is sufficient to reduce the phase voltage to the bridge operating voltage.

Thyratron Circuit:

The FG-57 thyratron appears to be satisfactory for this problem. It is a mercury-vapor negative-grid rectifier rated at 2.5 amperes average current, 15 amperes peak current and 200 amperes maximum surge current. It can withstand a maximum peak anode and inverse peak voltage of 1000 volts and the heater requires 4.5 amperes at 5 volts. Prior to operating this tube it is recommended that the heaters be operated for 5 minutes. The normal peak voltage drop across the tube is 16 volts.

If the phase voltage, E_{on} , is applied to the lamp bridge then the line voltage, E_{ac} , which leads E_{on} by 180° , is required for the thyratron anode supply voltage. The anode voltage is calculated as follows:

Maximum average voltage required to deliver 3.0 amperes to a field of 69.5 ohms is

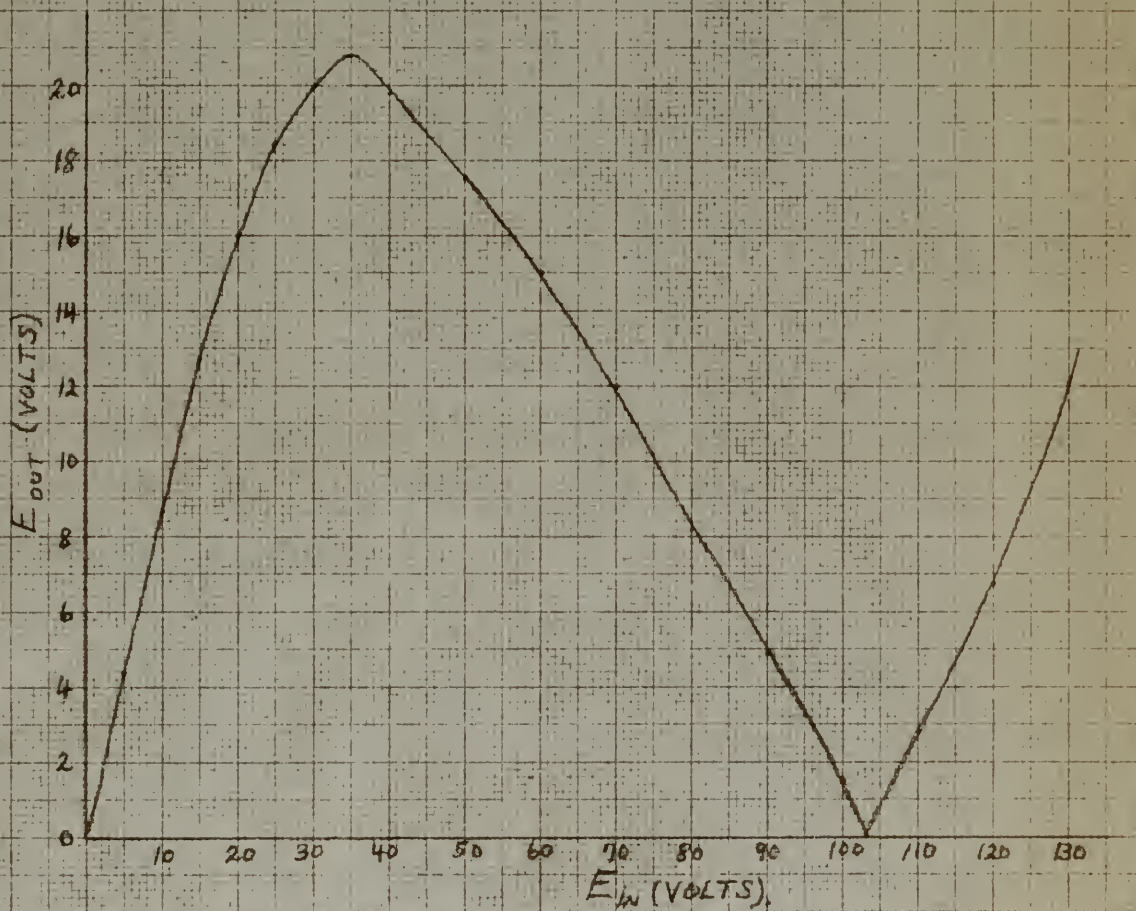


FIG. 10-VOLTAGE CHARACTERISTICS OF 75 WATT TUNGSTEN AND 120 WATT CARBON LAMP BRIDGE.

$$3.0 \times 69.3 = 208 \text{ volts}$$

Amplitude of half sine wave required for this maximum average voltage is

$$E_m = \frac{\pi}{2} E_{av} = \frac{\pi}{2} \times 208 = 327 \text{ volts}$$

The rms voltage is $\frac{327}{\sqrt{2}} = 231 \text{ volts}$.

The expected drop across the tube is $\frac{16}{\sqrt{2}} = 11.3 \text{ volts}$, giving a value of 242.3 volts rms as the required anode supply voltage. Since the thyratrons are to be operated as a full wave rectifier, the secondary winding of the transformer whose primary is connected across the 208 volt line voltage, ac, must deliver twice the above voltage or 484.6 volts, center-tapped. A 1-kva, 220:660-volt, center-tapped transformer should be satisfactory for this problem.

Grid Control Circuit:

The grid control circuit consists of a small 1:5 step-up, center-tapped transformer with the primary connected across the output of the lamp bridge and the secondary terminals each connected in series with a 47,000 ohm resistor to the grids of the thyratrons in such a manner that each grid voltage lags its respective anode voltage by 150° . The center tap of the secondary is connected to the two thyatron cathodes. This arrangement permits grid control similar to that shown in Fig. 5(b). The purpose of the 47,000 ohm resistors is to restrict the flow of grid current.

2.0 x 0.8 = 1.6

Results of this also have remained for the reason

stated above is

$$E = \frac{\pi}{2} \approx \frac{\pi}{2} \approx 1.57 \approx 1.57 \text{ rad}$$

The two values are $\frac{\pi}{2} \approx 1.57$ and $\frac{\pi}{2} \approx 1.57$

The maximum value of the function is $\frac{\pi}{2} \approx 1.57$ when

divides π into two equal parts and the function value

is $\frac{\pi}{2}$. Since the function is $\frac{\pi}{2}$ at $\frac{\pi}{2}$

and $\frac{3\pi}{2}$ we conclude that the function is $\frac{\pi}{2}$ at $\frac{\pi}{2}$

and $\frac{3\pi}{2}$ and is $\frac{\pi}{2}$ at $\frac{\pi}{2}$ and $\frac{3\pi}{2}$

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and

Heater voltage may be obtained from the alternator phase voltage or from the 113-120 volt commercial supply through a standard filament transformer rated at 5 volts and at least 9 amperes. A 25 ohm, 25 watt potentiometer in the primary of the filament transformer may be necessary to produce an output of 5 volts when the phase voltage is used. The complete circuit diagram is shown in fig. 11.

The first volume may be obtained from the University
 Press of the United States of America, Washington, D.C.
 through a special arrangement with the publisher
 and at least a copy. It is not, however, available
 in the library of the University of California at Los Angeles
 nor to anyone in need of a copy and has been ordered
 in need. The complete series of books is 10. 11.

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 some additions and changes. It is not, however,
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 books is 10. 11. 12. 13. 14. The fifth volume
 of the series is 10. 15. It is a continuation
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 material as the fourth volume but with some
 additions and changes. It is not, however,
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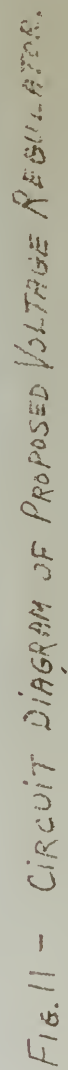


FIG. 11 - CIRCUIT DIAGRAM OF PROPOSED VOLTAGE REGULATOR.

CONSTRUCTION

The regulator was constructed on a breadboard, a photograph of which is shown in Fig. 12 (b). All components used were as designed, except the anode supply voltage transformer T_p . A 250:460-volt step-up, center-tapped transformer rated at 1-kva was available and in view of the fact that the design of the circuit was based on the pessimistic method of calculating voltage regulation, it was hoped that this transformer would be adequate for testing the circuit. Performance tests later proved that it was adequate for regulation between the range of 0.5 lagging and 0.5 leading with a 7.5-kva load, but would supply only 2.65 amperes to the alternator field instead of the desired 3.0 amperes.

The heater and cathode of the 6C-57 thyatron tube are connected internally. Since these tubes have their cathodes connected at a common point in this circuit, care must be taken to insure that the heater terminals of one tube are connected to the corresponding terminals of the second tube to prevent a short circuit.



Fig.12(a) - 12.5-kva General Electric alternator and motor.

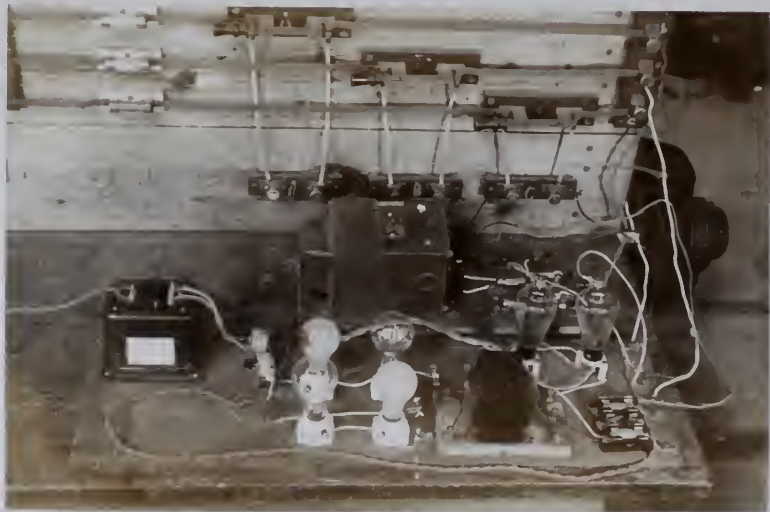


Fig. 12(b) - Breadboard arrangement of voltage regulator.

PERFORMANCE TESTS

In order to test performance, the regulator was placed in operation and the field rheostat of the alternator field was adjusted such that the regulator supplied 0.8 ampere to the alternator field and the separate direct current supply voltage provided the remainder (about 0.8 ampere) at no load. A 5-kva synchronous motor driving a direct current generator was selected as the alternator load. The load applied to the direct current generator was a lamp bank. The generator load was so adjusted that the alternator supplied 3.75-kva to the synchronous motor at unity power factor. By decreasing and increasing the field current of the synchronous motor the current was made to lag and lead the terminal voltage, respectively. The synchronous motor armature current was varied from 10.4 amperes (the value for 3.75-kva at unity power factor) to 20.8 amperes (the value for 7.5-kva at 0.5 power factor) for both the leading and lagging cases. The line voltages were measured with a Weston 300 volt voltmeter and the alternator rotor speed with a tachometer. The results are shown in the following table.

[illegible]

Load	Power Factor	Line Voltages			Rotor Speed (RPM)
		ab	ac	bc	
N.L.		208	208	208	1255
3.75-kva	1.0	208	208	208	1200
7.5 -kva	0.5 lag	208	208	208	1190
7.5 -kva	0.5 lead	208	208	208	1190

There was no motion of the voltmeter needle detected when changing power factors except when quickly shifting to the 0.5 lagging condition and then it was noted that the needle momentarily dropped about 0.5 volts and then returned to the value of regulated terminal voltage.

The wave forms of the line and phase voltages were observed on both a cathode ray oscilloscope and the General Electric Oscillograph for all the above conditions and there was no distortion noted. Oscillograms of the line voltage, ac, at no-load and 0.5 power factor lagging are shown in Figs. 13(a) and 13(b), respectively and the phase voltage, oa, at 0.5 power factor lagging in Fig. 13(c). The presence of the 33rd harmonic in the terminal voltage is very evident in Fig. 13(a).

With the regulator operative and the alternator at no-load, the field current wave form was observed on the oscillograph and an oscillogram made. As shown in Fig. 13(d) the wave form is essentially direct current with a

Year	Line	Year	Line
1950	1951	1952	1953
100	100	100	100
100	100	100	100
100	100	100	100
100	100	100	100

There are no other of the following items in the
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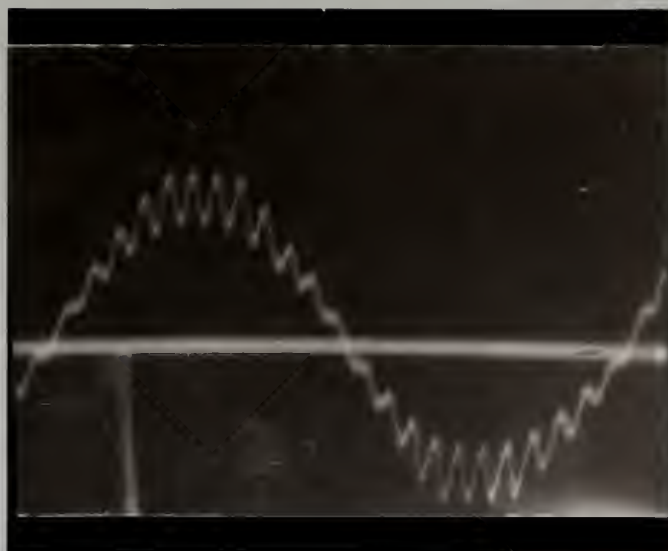


Fig.13(a) - Oscillogram of line voltage ac at no-load.

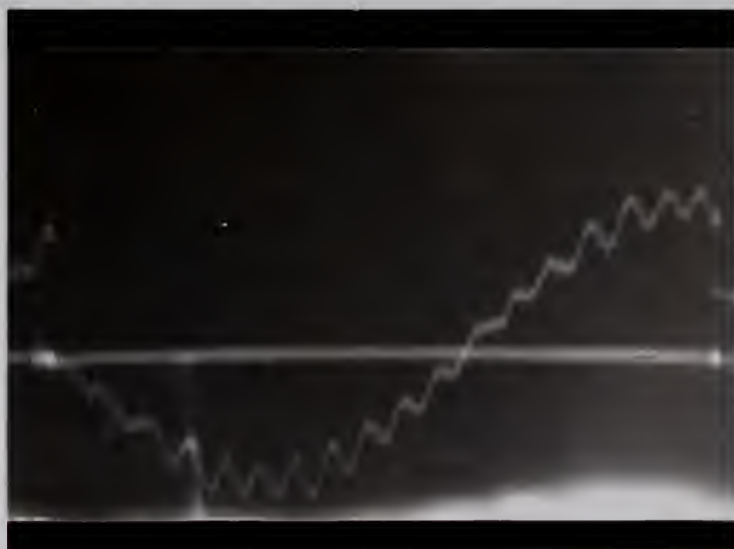


Fig. 13(b)- Oscillogram of line voltage ac at 7.5-kva, 0.5 lagging power factor.

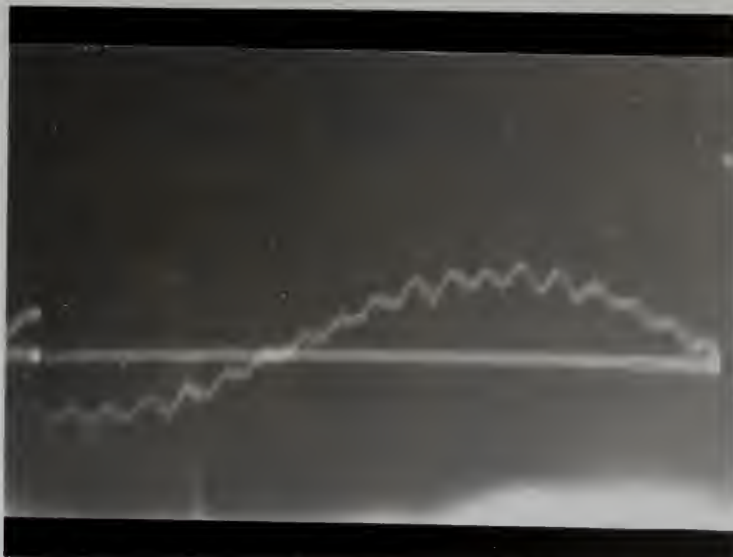


Fig.13(c)- Oscillogram of phase voltage on at 7.5-kva, 0.5 lagging power factor.

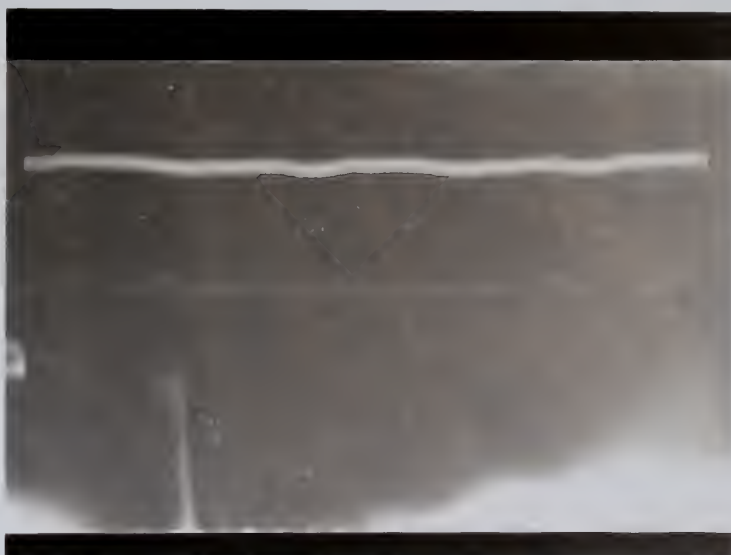


Fig. 13(d)- Oscillogram of field current at no-load.

small 120-cycle ripple.

The above tests were conducted with an alternator phase supplying the thyatron heater voltage. They were repeated with the heaters drawing current from the commercial supply and there were no observed changes in the alternator regulation. For satisfactory operation the voltage applied to the lamp bridge is about 163.5 volts.

Small 100-page volume.

The above books were combined with an illustration
book containing the illustrations of the various
plants with the names of the plants in the different
languages and their uses in the different
countries. For information regarding the plants
for the book please in your letter.

CONCLUSIONS

The regulator described in this paper provides very close voltage regulation over a wide range of power factors without any noticeable distortion in the terminal voltage wave form. It is noiseless in operation and contains no moving parts. The circuit is simple and requires a minimum of components, all of which are standard types commercially available at an economical price. There are no batteries required as is the case in many existing voltage regulators and the only parts that may need replacing are the four lamps in the voltage-sensitive circuit and the two thyatrons, but this should be necessary only after long periods of use. After initial excitation this regulator may be used as the alternator exciter, supplying all the field current. There is only one simple adjustment of the regulator required and that is the potentiometer, P_1 , which controls the voltage applied to the lamp bridge. After this has once been adjusted to the proper terminal voltage of the alternator, no subsequent adjustment should be necessary.

All factors considered, this type of voltage regulator appears to be the solution for a simple, rugged and economical regulator for small alternators at a small

initial cost. It is estimated that this voltage regulator may be constructed for as little as \$75.00

Unfortunately this regulator has its disadvantages and limitations. In its present form it is limited to a maximum current of 3.0 amperes. However, this can be easily increased by using a larger step-up transformer, T_2 , but care must be taken to see that the current through a single thyatron does not exceed 4.5 amperes average. There are two disadvantages that may be eliminated by a small addition to the existing circuit arrangement. The heaters of the thyatrons must be heated for a period of 5 minutes prior to the application of anode voltage and the field current supplied by the separate direct current source must be decreased when the regulator is placed in operation. This may be done automatically by the use of a motor-driven time delay relay that closes five minutes after the heater voltage has been applied. When the relay closes, the thyatron circuit is closed and at the same time an additional resistance is inserted in series with the field rheostat that reduces the value of its current. A satisfactory motor-driven time delay relay may be purchased for about \$15.00. This small additional expense is strongly recommended and will eliminate a possible personnel error that

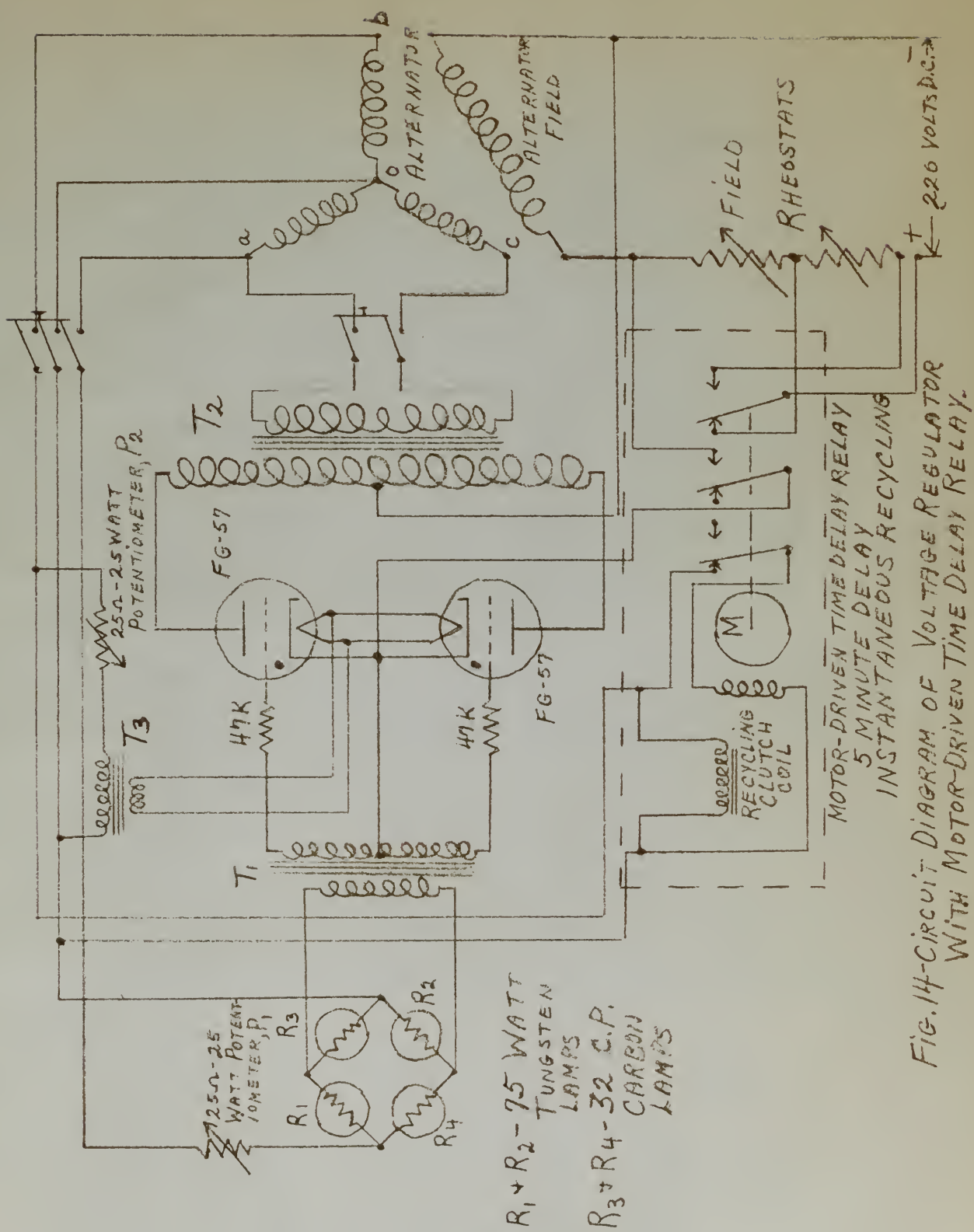


FIG. 14-CIRCUIT DIAGRAM OF VOLTAGE REGULATOR
WITH MOTOR-DRIVEN TIME DELAY RELAY.

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VIII

The author was born on February 4, 1916 in Rome, Georgia and received his secondary education in Atlanta, Georgia, graduating from the Technological High School in 1935. He received his Bachelor of Science Degree from the United States Naval Academy, Annapolis, Maryland in 1938. He engaged in his professional duties as a line officer in the United States Navy from 1938 to July 1946 when he entered the United States Naval Postgraduate School, Annapolis, Maryland. In September 1947 he entered the Graduate School of Engineering of The Johns Hopkins University.

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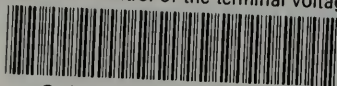
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